CHAPTER 2

EQUIPMENT SENSITIVE TO FREQUENCY AND VOLTAGE LEVELS

2-1. Theoretical overview.

Equipment sensitive to frequency and or voltage is designed to operate within certain tolerances. Most equipment is sensitive to large changes in the supply voltage level because more current will flow through a device when the voltage level of the supply is increased (the current through the device is equal to the voltage across the device divided by the impedance of the device). When a larger current flows, the heat dissipated in the device increases (the heat dissipated by the device is proportional to the square of the current). Thus, doubling the voltage will typically double the current, resulting in the device dissipating four times the heat. Most devices cannot tolerate this amount of heat and cannot operate reliably with a supply voltage level more than 10 percent or so higher than their rated voltage.

a. An additional complication arises in the case of devices that use magnetic coupling. Since most electrical equipment depends on a magnetic field as the medium for transferring and converting energy, the following paragraphs discuss a basic transformer to explain how the magnetic circuit depends on the frequency and amplitude of the applied voltage.

b. A transformer enables electrical energy to be transferred with high efficiency from one voltage level to another at the same frequency. Consider a simplified view of a transformer with a sinusoidal voltage source, *v*, applied to the primary circuit and the seconday circuit open, as shown in figure 2-1. The operation of the transformer depends on several natural laws including the following—

(1) A sinusoidal, time-varying flux, Φ, linking a conducting circuit produces a voltage, *e*, in the circuit proportional to $d\,\Phi/dt$ (i.e., Faraday's law of induction).

(2) The algebraic sum of the voltages around any closed path in a circuit is zero (i.e., Kirchhoff's voltage law).

(3) The voltage, *v*, in a circuit induced by a changing flux is always in the direction in which current would have to flow to oppose the changing flux (i.e., Lenz's law).

c. When the sinusoidal voltage, *v*, is impressed onto the primary electrical winding of N_1 turns, it is expected that a sinusoidal current, *I*, will begin to flow in the circuit, which in turn will produce a sinusoidally varying flux, Φ. For simplicity, it is assumed that all of the flux set up by the primary circuit lies within the transformer's iron core and it therefore links with all the turns of both windings. If the flux at any instant is represented by the equation:

$$\Phi = \Phi_m \sin 2\pi\, ft$$

where:

Φ_m = the maximum value of the flux
f = the frequency
t = time,

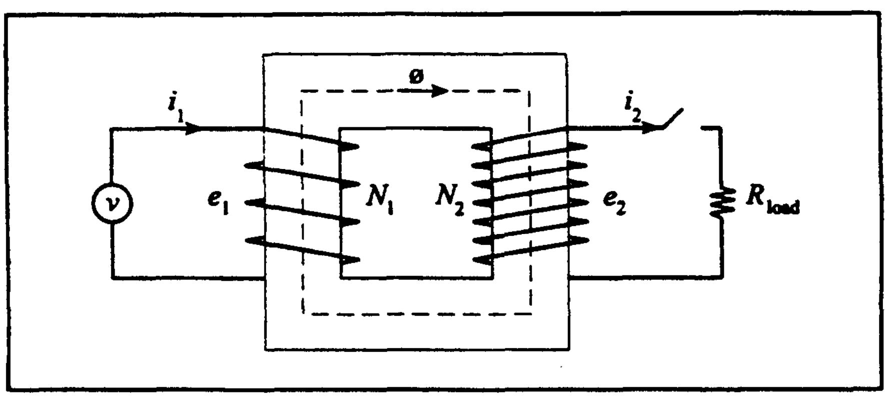

Figure 2-1 Simplified two-winding transformer

it follows from Faraday's law (i.e., $e = N\, d\,\Phi/dt$) that the instantaneous voltage e_1 induced in the primary winding is:

$$e_1 = 2\pi f N_1 \Phi_m \cos 2\pi f t$$

The polarity of e_1 will be according to Lenz's law, and hence will be in opposition to the impressed voltage, v (figure 2-1). The root mean square (rms) value of e_1 is

$$E_1 = (2\pi/\sqrt{2}) f N_1 \Phi_m = 4.44 f N_1 \Phi_m$$

d. Remembering Kirchhoff's voltage law, and assuming that the winding resistance is relatively small, E_1 must be approximately equal to V, where V represents the rms value of the applied voltage. One important result from this equation is that the value of the maximum flux, Φ_m, is determined by the applied voltage. In other words, for a given transformer, the maximum value of the flux is determined by the amplitude and frequency of the voltage applied to the primary winding. The same flux that caused E_1 in the primary winding will also induce a voltage across the terminals of the secondary winding. Thus, the only difference in the rms values of the two voltages will come from the difference in the number of turns. If the secondary winding has N_2 turns, the seconday voltage can be written as:

$$E_2 = 4.44 f N_2 \Phi_m$$

Dividing Equation 3 by Equation 4 gives the familiar relationship:

$$E_1/E_2 = N_1/N_2$$

e. Consider next when the transformer is loaded with a resister R_{load} by closing the switch in the secondary circuit. If the core flux is in the direction indicated (with the flux increasing), then by Lenz's law, the polarity of E_2 will be such that current I_1 will flow in the secondary winding in attempt to decrease the core flux. The amount of secondary current that will flow will depend on the value of R_{load} (that is, $I_2 = E_2/R_{load}$), and the power delivered to the load will equal $E_2 I_2$. It is important to understand the mechanism by which the power is transferred from the primary circuit to the load. Consider a situation when current is suddenly allowed to flow in the secondary winding by closing the switch. As mentioned previously, the action of this current will be to decrease the core flux. Decreasing the core flux would lower the value of E_1, which would be in violation of Kirchhoff's voltage law (KVL). Since KVL must be satisfied, more current must flow in the primary winding. The steady-state result is that the primary current will increase to the value sufficient to neutralize the demagnetizing action of the secondary current. It is important to realize that the resultant flux in the core remains the same regardless of the loading on the transformer. If the level of core flux were to vary with load, then E_1 and E_2 would also vary, which is contrary to what is observed in practice.

f. An iron core is used in transformers because it provides a good path for magnetic flux and directs the flux so it predominantly links all of the turns in each winding. However, the core has its limitations and can carry only so much flux before it becomes saturated. Core saturation occurs when all of the magnetic domains of the iron align, resulting in a condition in which no further increase in flux density over that of air can be obtained. Consider the magnetizing curve in figure 2-2, showing flux versus magnetizing current, where the magnetizing current i_m is the steady-state component of current

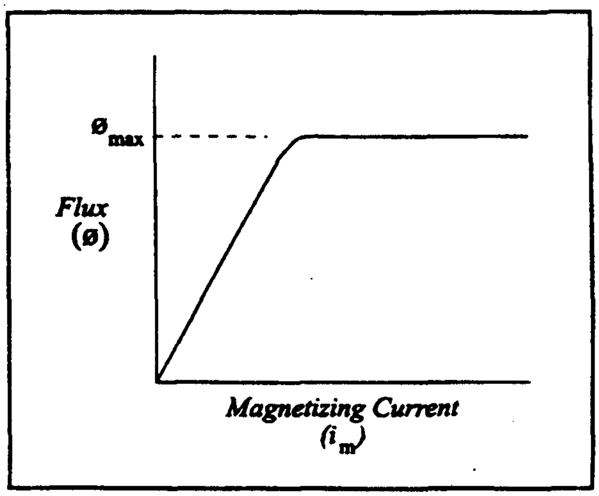

Figure 2-2. Magnetization curve for the transformer's iron core

required to establish the resultant flux level in the iron core for the transformer. It is typical for a transformer, or any other magnetic circuit, to be designed for operation close to the "knee" of this curve (i.e., Φ_{max}) to use as much of the iron core as possible. Beyond Φ_{max}, the iron saturates and it becomes extremely difficult to further increase the flux level. The curve implies that forcing the iron core into saturation can result in a significant increase in the value of the magnetizing current, and hence, can cause the windings to become overloaded and the transformer to overheat.

g. This study is concerned primarily with equipment sensitive to 50 Hz and voltage levels since the equipment will be used overseas where voltage frequencies and levels typically are different from those in the United States. This equipment could be listed by item, but a more useful format results when it is divided into classes and subclasses of equipment from which manufacturers for specific pieces of equipment can be easily selected. Following this format, listed below are the broad classes of equipment sensitive to 50 Hz and building voltage levels. Each section contains specific classes and subclasses of equipment. Additionally, each section describes why the equipment is sensitive to voltage frequency and or level. Equipment that does not readily fit into any other category is listed in paragraph 2-8.

2-2. Heating, ventilation, and air-conditioning (HVAC).

HVAC equipment includes boilers, furnaces, water chillers, humidifiers, fans, compressors, evaporators, and related equipment. Certain issues must be considered when using HVAC equipment in 50 Hz and alternate voltage environments, including the motor speed and step-down transformers for power supplies.

a. The objective of an HVAC system is to provide the necessary heating and cooling to a building according to the design specifications. Typically, alternating current (AC) motors are used in HVAC systems to drive fans, pumps, and compressors. When 60 Hz motor is run off a 50 Hz supply, the shaft speed of the motor is reduced by 5/6 since the motor speed is directly related to the frequency of the applied voltage. This speed will affect all direct-drive applications. For example, a pump that is directly coupled to the motor shaft will transfer less fluid over time if the shaft speed is reduced. Consequently, direct-drive HVAC applications must be derated to account for the reduced motor speed. However, for driven equipment that is tied to the motor through adjustable pulleys, the speed of the driven device can be increased to the necessary level.

b. Regardless of how the driven equipment is coupled to the motor, the 60 Hz motor must still operate within its rating in the 50 Hz environment. For the motor to deliver the same mechanical power at a lower speed, it must deliver more torque since output power equals torque times the shaft speed. If the motor delivers more torque, more current will flow in the motor and an overloaded condition may result. Hence, a 60 Hz motor may have to be derated to handle the extra current flow.

c. Another concern with operating a 60 Hz motor with a 50 Hz voltage source is with saturating the iron core of the motor. Like the transformer, the maximum value of flux in the core depends directly on the amplitude of the applied voltage and inversely on the frequency. Assuming that the same voltage level is applied to the 60 Hz motor in the 50 Hz environment, the reduction in frequency to 50 Hz would require an increase in core flux of 20 percent (that is, 6/5 of its 60 Hz level). If the iron core of the motor is unable to provide the extra flux, the core will saturate, and a significant increase in the stator currents can result, causing the motor to overheat.

d. Step-down transformers typically are needed to transform local voltage levels to the levels the equipment is designed for. In most cases, the equipment contains some sort of step-down transformer that typically has to be changed to convert the higher input voltage to the same output voltage. In cases where no step-down transformer is in the equipment, one must be added to avoid burning out components by subjecting them to a higher supply voltage. Determining the need for a step-down transformer and adding it to the equipment is easily accomplished, and is discussed further in chapter 3. Equipment that cannot be purchased with the precise specifications needed must be purchased in U.S. specifications and then derated as described in chapter 3.

2-3. Electrical distribution and protection.

Electrical distribution equipment includes transformers, panelboards and switchboards, generators, transfer switches, capacitors, and related equipment. Electrical protection devices include fuses, circuit breakers, relays, reclosers, and contactors. The devices have different sensitivities to supply voltage and frequency, and are discussed below.

a. Electrical distribution. As mentioned earlier, transformers are sensitive to the frequency and amplitude of the supply voltage. Using a 60 Hz transformer in a 50 Hz electrical environment can cause the core of the transformer to saturate, overheating the transformer. Other than the potential problem with saturation, the transformer should be fully capable of supplying the nameplate rated load. Most transformers are available in 50 Hz or 50/60 Hz configurations, so saturation should not be a problem.

(1) Panelboards, switchboards, and load centers are generally not sensitive to supply frequency, except when protective devices such as circuit breakers are included in them. These items can be acquired readily in a wide variety of voltage ratings; therefore, supply voltage does not pose a problem.

(2) General output voltage can be increased or decreased by using an appropriate transformer. However, since generators are typically used to supply backup power when the utility power source fails, and or are used in addition to the utility power source, it is necessary for the generator to provide a 50 Hz voltage source to match the utility supply. Therefore the user must purchase a generator configured for 50 Hz operation.

(3) Automatic source transfer switches are sensitive to supply voltage frequency and amplitude because they are electronically controlled and have power supplies that expect to operate on 60 Hz and rated voltage. Once again, supply voltage level is not a problem since transformers are available to adapt voltage levels. Supply frequency, however, may be a problem depending on the type of power supply the electronics use.

(4) Related equipment includes meter centers, and sockets or receptacles. Meter centers are sensitive to voltage level and frequency. Consequently, using a 60 Hz meter center in a 50 Hz environment may result in inaccurate readings. However, meters are readily available in a variety of voltage levels and 50 Hz configurations.

(5) Sockets or receptacles are needed when foreign consumer products are to be used with the power system. Receptacles are configured for different voltage levels, and these configurations vary in different countries. It is important that the standard receptacle style for a given voltage be used to avoid confusing the user and creating a potential safety hazard.

(6) Capacitors are used in an electrical distribution system to adjust the power factor or phase angle between the voltage and current waveforms. It is desirable to have a phase angle close to zero, or a power factor close to one so that most of the power transferred to the load is real power. Real power is the only part of the total kilovolt-amperes transferred that can do work. The balance is called reactive power and cannot do any useful work. The operation of a capacitor depends on the supply frequency, since a capacitor's impedance, X_C, is related to the capacitance and frequency of the current passing through it by the equation $X_C = 1(j2\pi fC)$, where C is the capacitance in farads and j equals the square root of -1.

b. Electrical protection. Electrical protection devices vary in their sensitivity to supply frequency. All protection devices are available in a wide range of voltage ratings so the level of the supply voltage is not a concern. The main concern with protection devices is the change in response time from 60 Hz to 50 Hz. These devices are coordinated to protect the distribution system from faults (shorts or spikes) but are connected so they do not trip when anticipated voltage spikes (that is, motor starting) occur. The power system design engineer must be sure to use the proper trip curves for the environment when coordinating protective devices. Trip curves for 50 Hz are readily available from vendors contacted in this study. The only device designed differently for 50 Hz and 60 Hz is the circuit breaker.

2-4. Medium voltage distribution equipment: 50 Hz → 60Hz.

In this section medium voltage transformers, switchgear and associated auxiliary devices will be examined with respect to frequency and voltage changes.

a. Medium voltage distribution transformers. Distribution transformers are key components in any electric power distribution system. It is important that they are properly matched to their environment. Issues related to operating a 60 Hz transformer from a 50 Hz power source were discussed earlier in this manual. The emphasis here will be on discussing issues concerning operating 50 Hz transformers in a 60 Hz environment.

(1) An important parameter to consider when operating a transformer, or other iron core-based devices, is the ratio of amplitude to frequency of the applied voltage. The ratio obtained using the nameplate rated voltage and frequency should be compared with the ratio available at the proposed site. If the ratio is less than or equal to that obtained using the nameplate quantities, magnetic saturation will not be a problem at the new site. Any time the ratio is higher than nameplate, the manufacturer should be contacted to ensure that the transformer has enough reserve available to accommodate the increase in operating magnetic flux density.

(2) For example, consider a transformer that is brought over from Germany where it was used on a 10 kV, 50 Hz distribution system. It was determined that the electrical insulation system of the transformer was rated for 15 kV. It is desired to use the transformer on a 13.8 kV, 60 Hz system. Considering the magnetic circuit, the volts-per-hertz ratio of the 50 Hz transformer is 200 (i.e., 10 kV/50 Hz). On the new supply the ration would be increased to 230 (that is, 13.8 kV/60 Hz), requiring a higher magnetic flux density in the iron core. This increase could potentially saturate the iron core and overheat the transformer. Alternatively, this

transformer could be used on a 7.2 kV/60 Hz system (120 volts-per-hertz ratio), where saturation would not be a problem.

(3) A few words should be mentioned concerning iron core loss in transformers. The two primary components of core loss are eddy-current loss and hysteresis loss. Eddy-current loss is the term used to describe the power loss associated with circulating currents that are found to exist in closed paths within the body of a iron material and cause undesirable heat production. Hysteresis loss represents the power loss associated with aligning and realigning the magnetic domains of iron in accordance with the changing magnetic flux. Both components are dependent on the frequency, as shown in the following equations:

$$P_{eddy\text{ - }current} = K_e f^2 B^2{}_m \tau^2 v$$

$$P_{hysteresis} = K_h f B_m^2 v$$

where,

K = constant value dependent upon material
f = frequency of variation of flux
B = maximum flux density
v = total volume of the material
τ= lamination thickness.

(4) It should be noted that, even though frequency increases when using 50 Hz transformers on a 60 Hz-based system, the voltage-to-frequency ratio will typically be lower, and hence, the maximum flux densities B will be lower. The result is that core-losses will generally not increase as a result of the higher frequency used.

(5) Other key parameters are voltage and current. To maintain insulation system integrity, rated voltage and/or current for the transformer should not be exceeded. A transformer can be operated on lower than rated voltage; however, its current rating must not be violated. Also, the secondary voltage must be matched to the proper voltage levels.

(6) In addition to having an iron core, windings, and insulation system, distribution transformers may include tap changers and auxiliary devices. Auxiliary devices might include fans, current transformers, pressure relief devices, and lighting arresters. Once again, attention should be focused on devices that use a magnetic field for transferring or converting energy, such as instrument transformers and small motor drives. Even if the voltage-to-frequency ratio is found to be lower, manufacturers should be contacted to make sure that all linear and rotating drive mechanisms will develop adequate force and torque to function properly.

b. Medium voltage switchgear. Switchgear is a general term covering switching and interrupting devices alone, or their combination with other associated control, metering, protective, and regulating equipment. Common switchgear components include the power bus, power circuit breaker, instrument transformers, control power transformer, meters, control switches, protective relays and ventilation equipment. The ratings of switchgear assemblies are designations of the operational limits under specific conditions of ambient temperature, altitude, frequency, duty cycle, etc. For example, the performance of some 50 Hz magnetic type circuit breakers may be altered slightly when operated on a 60 Hz power system. Switchgear manufacturers should always be consulted to identify the frequency response of circuit breakers and all auxiliary devices.

2-5. Safety and security equipment.

Safety and security equipment includes fire detection systems, burglar alarm systems, doorbells, and surveillance systems. This equipment typically operates on low voltage, either alternating current (AC) or direct current (DC), generated initially by a power supply. Acquiring the proper power supply to convert from the supply voltage to the low voltage that these systems expect (typically 6 to 12 VAC or VDC) is the key to proper operation of these systems in foreign environments. Power supplies of 50 Hz/120 VAC usually are available from vendors of these systems, and a transformer can be used to step a 240 VAC supply down to a 120 VAC foreign environment. Therefore, derating is not necessary for these items, although a transformer may be needed to step high voltage supply levels down to 120 VAC for the power supplied to these systems. Most vendors of safety and security equipment can configure their equipment to 50 Hz and a variety of voltage levels.

2-6. Communication equipment.

Communication equipment encompasses public address systems and sound systems, both of which operate on a low-voltage DC supply generated by a power supply. Power supplies are available to operate on 50 Hz and 240 V supply voltages. In cases where only 120/50 Hz supplies are available, a step-down transformer can be used to step a 240 V supply down to 120 V. The vendors contacted in this study have stated that they provide 50 Hz power supplies.

2-7. Lighting.

Lighting can be divided into incandescent, fluorescent, and high intensity discharge (HID) categories. Incandescent lighting is not frequency-sensitive, whereas fluorescent and HID lights are started by a ballast that is sensitive to voltage level and frequency.

All types of lighting are sensitive to the supply voltage level and cannot be derated for voltage. For example, subjecting a 120 V incandescent lamp to a 240 V source will result in the lamp burning twice as hot, causing rapid lamp failure. Subjecting the iron core ballast use in many HID and fluorescent fixtures to twice its rated voltage will saturate the ballast and will subject the fixture to much more than its rated current. As with transformers and motors, 60 Hz iron-core ballasts can also be saturated when operated at 50 Hz. At first thought, frequency dependence may not be os much of a problem with electronic ballasts since, in most cases, the AC voltage source is first converted back to a high frequency AC source, and therefore, the voltage source that is actually impressed across the lamp is decoupled from the 60 Hz AC source. However, the power supply used to power the electronics in these ballasts must be capable of 50 Hz operation.

2-8. Other electrical equipment.

Other electrical equipment includes motors, motor starters, computer power supplies, and clocks.

a. Typically, motor starters are sensitive to both supply voltage level and frequency. The most commonly used motor starters consisters of a coil, thermal overloads, and a set of contactors (contacts). The thermal overloads, which are essentially circuit breakers, and the contactors are rated to handle a certain amount of current. Since at 50 Hz, a motor of a given horsepower rating will draw more current than an identically-rated motor would draw at 60 Hz, the thermal overloads and the contactors must be sized accordingly.

b. Computer power supplies include voltage regulators, isolation transformers, transient voltage suppressor transformers, computer regulator transformers, and power conditioning transformers. Computer power supplies are sensitive to both frequency and voltage level.

c. Clocks are sensitive to supply frequency and voltage. Clocks rely on the frequency of the supply voltage to keep correct time, so a clock designed for 60 Hz will not keep correct time at 50 Hz. The motor that runs the clock is also sensitive to supply voltage level. Therefore, a clock must either be purchased configured for the supply voltage level, or a transformer must be used to convert the supply voltage level to the clock's rated voltage level. Clocks cannot be derated for frequency, and therefore clocks designed for 50 Hz must be purchased.